

FAR INFRARED RESPONSE OF THIN FILM $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ USING A FREE ELECTRON LASER

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The far infrared response of granular thin-film $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ superconductor has been investigated using long ($\approx 5 \mu\text{s}$) but sharply truncated free electron laser pulses in the frequency range between 50 cm^{-1} and 125 cm^{-1} . Under constant current bias, a fast response and a slow bolometric signal component could be identified in this energy range, which is below the BCS energy gap ($\approx 200 \text{ cm}^{-1}$). Measurements of the power dependences of the signal voltages showed that both the fast and the thermal responses are consistent with the predictions of the resistively shunted Josephson junction model.

Key words: High- T_c superconductors, FIR-detection, free-electron-laser

Introduction

There has been considerable interest in understanding the optical and infrared response of high- T_c superconductors. In previous investigations of thin granular films a wide range of response times have been observed. Slow signals, with time constants in the range of microseconds to milliseconds, were identified as a bolometric response arising from heating of the film. Fast signals in the far infrared (FIR), with time constants of nanoseconds, were attributed to several non-thermal mechanisms: an optical destruction of wave function coherence [1], the depairing of vortex-antivortex pairs [2], an optically induced charge imbalance in neighbouring superconducting grains [3] or infrared radiation generated currents in Josephson junctions inherent in granular films [4,5]. A drastic variation of the response time with frequency were found in $\text{Ti}_2\text{Ba}_2\text{Ca}_1\text{Cu}_2\text{O}_8$ films using FIR molecular lasers pumped by TEA CO_2 lasers [6]. Below a critical frequency $\nu_c \approx 100 \text{ cm}^{-1}$ only fast signals, with a time constant in the order of 1 ns, were observed. In contrast, above ν_c a slow response of bolometric character occurred. The transition frequency ν_c was identified with the energy gap value at the surface of superconducting grains. Recently non-thermal processes have been questioned by an investigation of the thermal boundary resistance of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ films and their substrate materials [7]. It was shown that a bolometric response may occur on a nanosecond time scale: thus thermal and nonthermal effects cannot be distinguished by the time constant alone.

In the present paper we report on measurements of the FIR response of thin granular film $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ using the University of California, Santa Barbara, (UCSB) Free Electron Laser (FEL). The sample was irradiated by long laser pulses truncated at the trailing edge by a rapid optical switch. Our results demonstrate that in the FIR both fast and slow signals of very different time constants are present at high powers, indicating two distinct signal generation mechanisms. The slow signal is readily identified as a bolometric response by the non-exponential decay which follows from one dimensional heat flow through the substrate to the cold finger [8]. Both types of signals show a nonlinear dependence on intensity which may be explained by the model of an effective resistively shunted Josephson junction which has the properties of a random array of junctions [9,10].

Experimental

$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ films were prepared on MgO substrates by excimer laser sputtering and subsequent annealing as described

previously [11]. By using X-ray diffraction the film was established to be single phased and c-axis oriented. Electron micrographs showed that the film consisted of an irregular array of grains between $1\text{ }\mu\text{m}$ and $10\text{ }\mu\text{m}$ in diameter. The film was shaped by excimer laser ablation into a bridge like structure, 1.9 mm long and $100\text{ }\mu\text{m}$ wide with contact pads at both ends. The resistance as function of temperature showed a smooth transition from the superconducting to the normal conducting state centered at 85 K . The onset of resistive current flow was at about 70 K for currents of $10\text{ }\mu\text{A}$ or less and decreased in temperature with increasing current.

The sample was mounted in a temperature variable cryostat with optical access. A current bias of $400\text{ }\mu\text{A}$ was applied in series with a $50\text{ }\Omega$ load resistor and the increase of the voltage across the sample upon irradiation was recorded by a digital storage oscilloscope. The laser radiation was focused on the sample with a focal spot diameter of about 3 mm . The intensity and temporal behaviour of the laser pulses were monitored by a fast pyroelectric detector and a Schottky diode, respectively. The peak power and intensity of the pulses at the sample were between 2 kW cm^{-2} and 24 kW cm^{-2} , depending on wavelength, with an untruncated pulse duration of $5\text{ }\mu\text{s}$. However, the laser beam was transmitted through a optical switch which consisted of a silicon wafer irradiated by either 400 ps or 10 ns pulses of $\lambda = 532\text{ nm}$ radiation. The switch chops the FIR pulse to zero within the visible pulse duration. Thus, by this method both slow bolometric and fast non-thermal signals may be simultaneously investigated at the same time. The FEL was tuned between $200\text{ }\mu\text{m}$ (50 cm^{-1}) and $80\text{ }\mu\text{m}$ (125 cm^{-1}). As no sharp spectral structures in the response are expected, wavelengths lying outside strong water vapour absorption bands were selected.

Results

In Fig. 1 two typical signal pulses as function of time at a temperature $T = 10\text{ K}$ are shown for a film of $\approx 0.3\text{ }\mu\text{m}$ thickness at $\lambda = 200\text{ }\mu\text{m}$ and $84\text{ }\mu\text{m}$. These recordings were obtained using the 10 ns switch. When the laser pulse is terminated the signal first drops rapidly and then proceeds into a long tail of several μs decay time. The sharp signal decrease corresponds to the fast response and the tail is the bolometric signal. The drop of the fast response is equal to the switching time of the radiation. Applying the 400 ps switch, a 1 ns upper limit of the time constant could be established which was determined by the electronic circuitry bandwidth. No effort has been made to improve the temporal resolution.

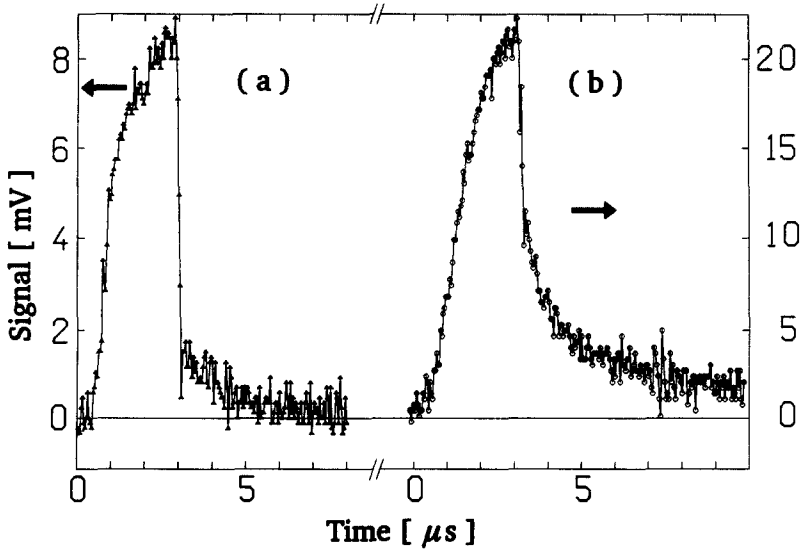


Fig. 1 – Response of a $\approx 0.3\mu\text{m}$ thick film to laser pulses truncated by a semiconductor switch at $T = 10\text{ K}$. Wavelength and peak power, respectively: (a): $200\mu\text{m}$, 0.5 kW ; (b): $85\mu\text{m}$, 2 kW .

The slow decay of the thermal signal is more pronounced for thicker films. Fig. 2 shows a recording of a pulse at $\lambda = 150\mu\text{m}$ with a film of about $1\mu\text{m}$ thickness. In the insert a semi-log plot of the signal pulse is shown which clearly proves that the decay of the slow response is non-exponential as expected for a bolometric signal [8].

The BCS energy gap of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ ($\approx 200\text{ cm}^{-1}$) is bigger than the quantum energies corresponding to all three wavelengths. The measurements therefore demonstrate that a bolometric response is present even below the energy gap. In Fig. 3 the power dependence of the signal at $\lambda = 150\mu\text{m}$ is shown. The fast and the bolometric response are separately displayed in a log-log plot. Guide lines for the eye are drawn in the diagram with slopes $1/2$ and $3/2$.

Discussion

For the fast signal the measurements confirm a square root dependence on incident power P for high power levels which

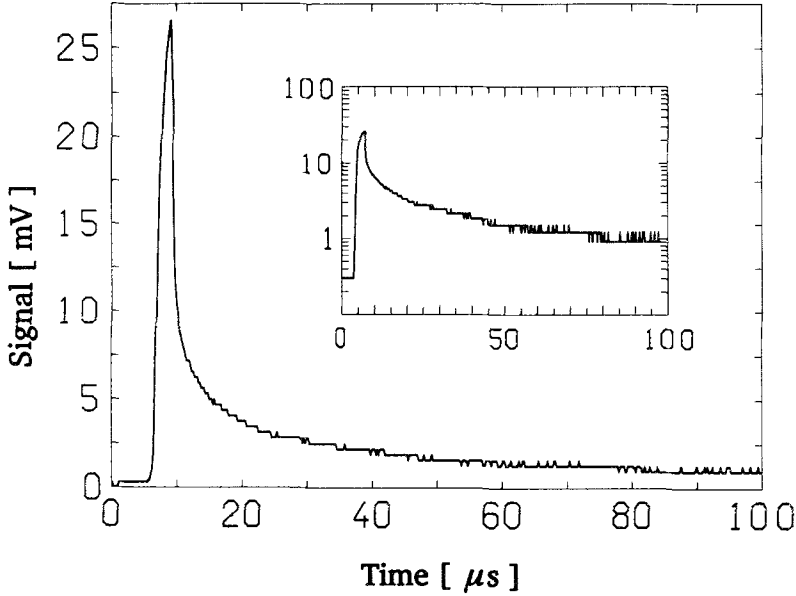


Fig. 2 - Response of a $\approx 1\mu\text{m}$ thick film at $150\mu\text{m}$ wavelength and $T = 10\text{ K}$. The insert shows a semi-log graph of the same pulse demonstrating the non-exponential decay of the slow signal.

approaches a linear relationship at low intensities. This behaviour is in agreement to previous investigations of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ films excited by an FIR molecular laser pumped by Q-switched CO_2 laser [5]. The power dependence has been attributed to FIR induced currents I_{rf} in a random array of Josephson junctions formed by grain boundaries. For frequencies below the energy gap and current amplitudes $I_{rf}/I_{c0} < 1$, the critical current I_c is reduced following $I_c = I_{c0} - \gamma I_{rf}$ where I_{c0} is the non irradiated junction critical current and γ is a constant depending on frequency. For constant current biasing conditions, this leads to a change of the sample resistance $\Delta R \sim I_{rf}$ which in turn causes a development of the signal voltage across the sample $\Delta V \sim P^{1/2}$ because $P \sim I_{rf}^2$. For low power, i.e. $I_{rf} \ll I_{c0}$, a linear dependence, $\Delta V \sim P$, of the signal on power is approached [12].

The slow response is found to depend superlinearly on irra-

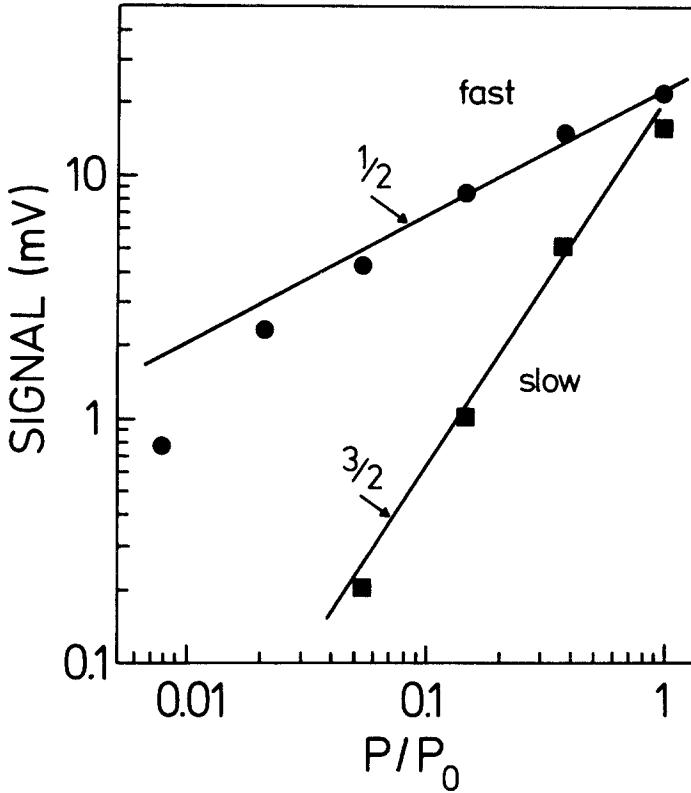


Fig. 3 – Fast and bolometric signal as function of beam power P in units of $P_0 = 2\text{ kW}$ at $T = 10\text{ K}$ and $\lambda = 150\text{ }\mu\text{m}$. The solid lines indicate slopes $1/2$ and $3/2$.

diation power, approximately like $\Delta V \sim P^{3/2}$. The decay of the signal is non-exponential indicating a bolometric response whose temporal behaviour is determined by heat diffusion. The decay time is much longer than the duration (typically 100 ns) of FIR pulsed molecular lasers. This fact and the superlinear power dependence may explain why no bolometric response has been observed [1,6] in measurements with FIR molecular lasers pumped by TEA or Q-switched low-pressure CO_2 - lasers. As the response time is larger than the duration of the exciting laser pulse, the peak signal is determined by the deposited energy rather than by the peak intensity

of the laser pulse. The energy per pulse of the free-electron-laser is at least two orders of magnitude larger than that of pulsed molecular lasers used previously [5,6,13], and thus the bolometric signals may be below the detectable limit in the latter measurements.

Bolometric signals in the FIR may be caused by dissipation of radiation power at quantum energies smaller than the energy gap yielding a heating of the film. Surface impedance measurements in the FIR and microwave regime have shown losses in high- T_c films even at low temperatures where a BCS superconductor should be totally reflecting [14,15]. This residual absorption strongly depends on the quality of the material and is minimal for epitaxial c-axis oriented films. Recently D. Miller *et al.* [16] demonstrated that the spectral dependence of the residual absorption of a variety of differently prepared $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ films may be quantitatively described by a model proposed by Hylton *et al.* [10]. The film is treated as network of weakly coupled superconducting grains. Grain boundaries form resistively shunted Josephson junctions and the grains are represented by a series dynamic inductance. Adopting this loss mechanism for the bolometric signal gives the dissipated energy to be proportional to $\Delta R I_{rf}^2$. The dissipative element R originates from the depression of the critical current by the incident radiation. Its value is proportional to the fast signal as shown above. Thus, in the power range where the fast signal is proportional to $P^{1/2}$, a $P^{3/2}$ dependence of the bolometric signal is expected. These power dependencies are in reasonable agreement to the experimental observations shown in Fig. 3.

Conclusion

In summary, the FIR optical response of thin current biased $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ films have been investigated by long FEL pulses with steeply truncated trailing edges. The signal fall time has two components, a fast drop and a slow bolometric decay with time constants of the order of ns and μs respectively. From the power dependence it is concluded that both signal components arise from a random array of resistively shunted Josephson junctions. The fast signal is caused by infrared induced currents in the junctions whereas the bolometric signal is due to heat dissipation in the junctions. To reveal the $P^{3/2}$ dependence on irradiation power of the thermal signal requires high energy laser pulses which are conveniently provided by the UCSB-FEL.

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